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Seabed and sub-seabed boulders as an engineering hazard in the marine environment; a risk mitigation strategy for subsea cables

Les risques techniques liés aux blocs rocheux de surface et enfouis dans l'environnement marin; une stratégie d'atténuation des risques pour les câbles sous-marins

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ABSTRACT: Every subsea cable development presents a unique set of conditions and constraints. The exact approach to seabed and sub-seabed boulder mitigation work is defined not only by the nature of the environment, but also the options open to the developer in terms of financial budgets and available construction timescales. Boulders represent a significant geohazard for trenching and installation operations of subsea cables. This paper proposes a comprehensive risk mitigation strategy for seabed and sub-seabed boulders in the marine environment. Once the magnitude of boulder risk is known through appropriate surveys and risk assessments, the following steps can be considered: avoidance, removal, reduction and/or relocation or remediation of residual risks. Working through these steps ensures a suitable mitigation strategy is followed, reducing the risk through adequate design, installation and remediation planning.

RÉSUMÉ: Chaque projet en mer présente un ensemble unique de conditions et de contraintes. L'approche exacte du travail d'atténuation des risques liés aux blocs rocheux pour tout type de développement est définie non seulement par la nature de l'environnement, mais aussi par les options ouvertes au développeur en termes de budgets financiers et de délais disponibles pour achever les travaux d'ingénierie. Les blocs rocheux présents sur le fond marin et enfouis représentent un risque géologique important pour les opérations de creusement de tranchées en mer et d'installation de câbles sous-marins. Cet article propose une stratégie globale d'atténuation des risques liés aux blocs rocheux de surface et souterrains dans l'environnement marin. Une fois l'ampleur de ces risques connue, grâce à des études et des évaluations appropriées, les options suivantes peuvent être envisagées: éviter, enlever, réduire et/ou déplacer ou remédier aux risques résiduels. Ces étapes permettent de définir une stratégie d'atténuation appropriée, grâce à une conception adéquate, au choix de l'installation adaptée et à la planification de la solution de mitigation.

Keywords: Boulder mitigation; mitigation strategy; surface boulders; sub-seabed boulders; subsea cables.

1 INTRODUCTION

Seabed and sub-seabed boulders pose a significant geohazard to a wide range of offshore wind activities, including trenching and installation of export and inter-array cables. In the marine environment, boulders are often found in areas previously influenced by glaciation, such as the North Sea, Baltic Sea, and East Coast of USA etc. The sediment formations containing boulders are often related to glacial features, such as moraines and outwash plains (Johnson et al., 1993). Glacial soils may consist of a mixture of sediments with a variety of degrees of sorting, including boulders (Clarke, 2018). These boulders can vary in shape and size, can be found at and/or below the seabed and can be isolated or in high density clusters (known as boulder fields). As per ISO 14688-1 (2017), boulders are defined as soil particles with diameter >0.20 m. However, for the purpose of this paper, and as it will be discussed in subsequent sections, mainly boulders with diameter >0.30 m are considered a risk to cable installation operations.

Where boulders are present, and as with any other hazard, the first step is identification and quantification of the risk across the site (Wetton et al., 2024). This information, together with knowledge on proposed operations and equipment limitations, will determine the impact, relative to size and density of boulders, and whether any mitigation is required.

If mitigation is required, measures such as, avoidance, removal/ relocation of boulders, reduction of the risk or/and remediation should be considered (Figure 1). Unanticipated requirements in overcoming boulder constraints may result in significant additional costs to developers and contractors, should the risk of boulders and a sufficient mitigation strategy not be identified from the early stages of the development.

The size and number of boulders, as well as whether they have been identified as isolated or in clusters, can significantly influence the methods used for mitigating the risk. Recommended best practises for subsea cables, such as the (DNV GL, 2021), highlight boulders as a geohazard that can affect cable routing, installation and protection, recommending the performance of boulder clearance campaigns, however, without presenting a recommended methodology to plan for remediation.

In this paper, the above-mentioned steps will be elaborated outlining a methodology for mitigating the risk of boulders to subsea cables.

It should be noted that a similar mitigation strategy can be suitable for boulder risk to offshore structure foundations, however this paper focuses only on subsea cables.

Figure 1. Boulder mitigation strategy.

2 MITIGATION STRATEGY

The selection of a suitable boulder mitigation strategy is governed by several factors which could include: boulder quantity, distribution, project location, commercial factors, project schedules, etc. Figure 1 outlines a proposed strategy method. Each step will be described in more detail in the subsequent sections.

2.1 Identify and quantify

The first step in the proposed mitigation strategy is to identify and quantify the boulders across the area of interest. This is achieved by planning a survey strategy ensuring the most suitable data is acquired by specifying appropriate survey techniques and correct resolutions (Carbon Trust, 2020). To ensure a suitable survey is being performed, the timing needs to be carefully considered. Prior to a survey, a cable corridor needs to have been defined with indicative cable burial and boulder clearance tools already in consideration (Wetton et al., 2024).

Once the data has been acquired, boulders are quantified by undertaking a 'boulder picking' exercise, an interpretive exercise where boulders are identified, located, and the dimensions measured to produce a boulder listing. This interpretive exercise should be tailored to a specific mitigation strategy it is targeting. For cable routing, a more efficient approach for quantifying the number of boulders, at an early stage, could be to focus on the areas posing the highest risk, e.g., large boulders >1.5 m and boulder fields. By only focusing on quantifying the critical areas, the picking exercise is less time demanding, and data could be available at an earlier stage without compromising understanding. At a later stage, data can be reinterpreted to a stricter specification, within a smaller study corridor once the preferred installation tool is selected. This approach could potentially save time and resource during the interpretation phase. As a development progresses the survey corridor may decrease from ~150 m to <20 m, rendering detailed interpretation outside of the reduced corridor obsolete.

Once the boulder listing is available, this can be used to estimate the likelihood of boulder encounter and impact of encountering areas with different boulder density (high to low), for each section of the proposed cable route.

2.2 Avoid

As with any hazard assessment, avoidance should be the first mitigation option, which in the case of subsea cables, is undertaken, where feasible, through route engineering (Figure 2). Route engineering is a process of designing the shortest and most practical cable route possible, whilst avoiding known physical risks. An outline of considerations is highlighted in (DNV GL, 2021).

Each identified risk is evaluated and assigned a design constraint. Constraints may be seen as "hard", must be avoided or as "soft", avoid if practical, as shown in Table 1.

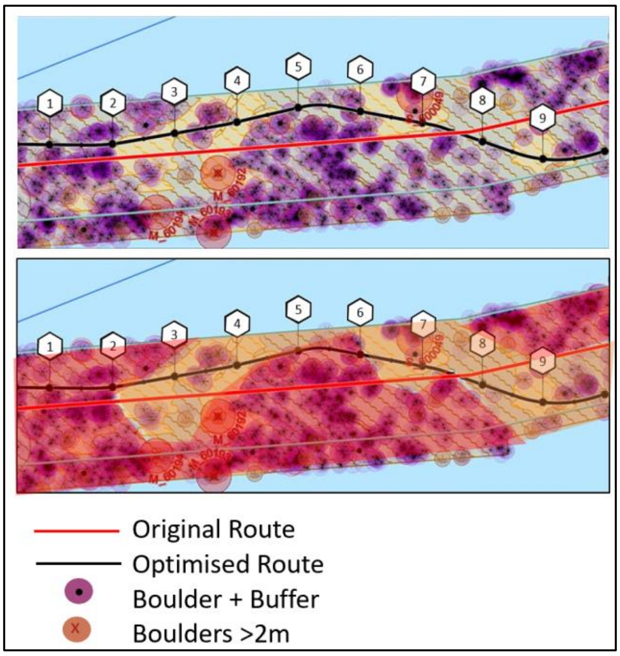

Figure 2. Route engineering example.

Table 1. Boulders as cable route constraints.

Individual Boulders	Boulder Fields	Constraint Level	
Size (m)	**Density**		
< 0.5	Low	Soft Constraint	**Low**
0.5 - 1.5	Medium	Soft Constraint	**Medium**
1.5 - 2	High	Soft Constraint	**Severe**
> 2	-	**Hard Constraint**	

In most cases, it is impractical to avoid every boulder, especially where there is the presence of boulder fields, hence why boulder fields are not a hard constraint in Table 1. Together with boulders, there are other constraints to consider, which may take precedence over boulders, such as unexploded ordnance (UXO) and cable installation limitations (e.g. maximum bend radius and turning radius of tool). The aim of route engineering is to identify the most favourable route by avoiding any hard constraints and as many soft constraints as possible. Where soft constraints are intersected, the shortest route through, should be selected. Alongside reducing the risk of surface boulders, route engineering may assist with the mitigation of sub-seabed boulders. Where areas of concentrated sub-seabed boulders have been identified route engineering can also work to avoid these.

In practice, it is often the case, possibly due to limitations in identifying sub-seabed boulders, that only surface boulder information is available for a project. Actions can be taken, such as avoiding formations known to contain boulders, which can be identified through developing a geological Ground Model early in the project. Predicting or avoiding sub-seabed boulders may not always be possible and thus the risk remains as a residual risk within a project.

2.3 Remove/Relocate

Following route engineering and especially if there were areas of boulders where avoidance was not possible, a boulder clearance campaign may be required. Clearance campaigns mainly target surface boulders with mitigation methods including Boulder Grab (BG) and Clearance Plough (CP). For sub-seabed boulders, clearance is generally more challenging with tools such as pre-lay/pipeline ploughs existing in the industry. The following sections summarise some of the possible clearance methodologies.

2.3.1 Boulder Grab (BG)

BGs are used to remove and relocate boulders along a cable installation corridor. They resemble a mechanical claw and are typically fitted with thrusters, ultra-short baseline (USBL) and video feed to aid positioning over the boulder. The boulder is captured within the claws and relocated, to a pre-agreed location, off the main installation corridor.

BGs are suitable for areas with lower density of boulders or individual boulders rather than large boulders fields, due to time taken for vessel positioning and the operations undertaken to remove and relocate the boulder. Typically, the maximum boulder size a generic BG can relocate ranges from ~2 to 3 m. This will significantly depend on the percentage of the boulder that is buried, as a suction force can be created, increasing the working loads for the equipment.

Minimum survey requirements for this operation would include exact location and dimension of the boulder to be removed. An understanding of shallow geology of the soil matrix and boulder rock type would be beneficial.

Typical time duration for the relocation of one boulder, using this method, is 30-60 mins, depending on the relocation area and other seabed constraints. Note this does not include transiting times between individual boulders.

2.3.2 Clearance Plough (CP)

For sites with higher densities of boulders, a CP may be more suitable. CPs are towed along the seabed pushing/relocating surface, or near surface, boulders to either side, leaving a 'cleared' corridor of ~15 m width with a maximum penetration into the seabed of ~0.2 m (depending on soil type). CPs are generally limited to boulders up to ~1.5 – 2.0 m in size and therefore if larger boulders are present at the site, this method would have to be used in conjunction with another, such as route engineering or a BG.

Minimum survey requirements for this operation would include location, including dimensions, of larger boulders (>1.5 m), location of boulder fields with density, high resolution bathymetric data and shallow geology information.

The operation speed of these ploughs is typically between 150-500 m/hr depending on the geotechnical conditions of the seabed and the density of boulders.

For boulder clearance within a Lease Area (i.e., for the inter-array cables), scheduling of the operations at the right development phase for the project should be considered. Preferably, seabed clearance operations should be carried out prior to installation. Should this operation be undertaken after the wind turbines generators (WTG) foundations have been installed, the vessel (and CP) would have to veer off a significant distance to avoid the structure and areas of seabed may be left uncleared which could later impact burial operations along the inter-array cable or require an alternative mitigation method.

2.3.3 Pre-Lay Plough (PLP)

PLP is a combined clearance and trenching plough, where the plough's share creates the "Y-shape" trench, with the mouldboards pushing the spoil away. PLPs are generally able to create a trench up to ~1.8 m deep, in a single pass. In certain conditions, the trenching capability may allow for mitigation of sub-seabed boulders, depending on the size and depth of the boulder. Advanced PLP systems also have the capabilities to include integrated backfill operations.

Similarly to the CP, the PLP requires the identification of boulders greater then ~1.5 – 2 m in diameter, as these will likely require a different mitigation measure. The scheduling should be considered, operations to be undertaken prior to construction of WTGs, as per the CP.

Similar survey requirements to the CP are required for a PLP, with the addition of more detailed understanding of the shallow geology to predict tow forces and speed. Available information on sub-surface boulders, i.e. density and expected dimensions, are also useful.

PLPs require much higher tow forces than CPs, especially in sandy soils, with some of the larger ploughs requiring up to 300 tonnes of towing force. This results in the need for more specialised vessels with higher bollard pull or the addition of tug vessels. These larger ploughs may also require an "A Frame" launch and recovery system with sufficient deck space for the large plough.

Due to the specialised nature of this tool, there is limited availability on the market and can often be in high demand, emphasising the need for early planning.

2.3.4 Summary of removal methodologies

When selecting the most suitable solution for boulder removal, boulder density and location of the boulders should be considered, and it is likely to significantly influence the decision. Figure 3 shows a schematic of how the number of boulders affects the clearance operations duration for a BG (green line) and CP (red line). As can be seen with ploughing, dependent on density, operation speed is relatively consistent. Although, there will likely be some variation depending on soil type. Whereas with the BG, clearance would be more effective in low density areas. Operation time would also be heavily dependent on the spacing of the boulders.

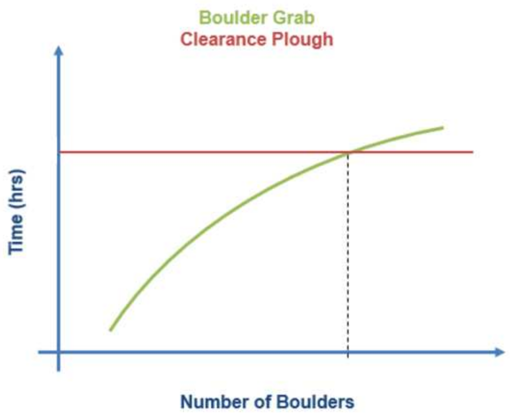

Figure 3. Effect of number of boulders to clearance operation timescales.

A brief suitability assessment for each of the methodologies is shown in Table 2. The table uses a traffic light ranking system for general suitability based on some of the main consideration factors; where green is high, orange is medium and red highlights low suitability for each solution. As can be seen, not one methodology is suitable for all factors. The final mitigation plan will likely include a combination of methodologies with the cable route zoned in accordance with the most suitable tool.

Table 2. Boulder clearance tools suitability assessment.

Consideration Factors	BG	CP	PLP
Time			
Cost			
Availability			
Sub-seabed boulder – clearance			
Efficiency – Higher density			
Efficiency – Lower Density			

2.4 Reduce

Detailed data on sub-seabed boulders are not always available. Consequently, even with the above mitigation measures of avoid and remove, the risk of sub-seabed boulders generally remains. The presence of sub-seabed boulders can result in reduced/no burial of a cable with contractors generally insisting on a *'Reasonable Endeavours'* clause within their contract.

Where sub-seabed boulders are expected, in order to reduce the risk, the selected cable installation tool should be considered based on the ground conditions and identified trenching risks (DNV GL, 2021). Some installation tools can be fitted with a structure, similar to a small scale 'clearance plough', to protect the installation tool from boulders.

Most installation contractors will highlight all boulders >0.3 m as potential risk to cable installation for all tools. However, some cable installation tools may be more suitable than others, e.g., a cable plough would likely be able to withstand larger boulders compared to other trenching tools. Table 3 below summarises the advantages and disadvantages, with regards to boulders, of the three most commonly used installation tools.

2.5 Remediate

Following the above mitigation steps, the risk to boulders should be considerably reduced. However, if boulders still pose a risk to a site and cannot be further mitigated against, additional costs should be factored into a project to allow for external protection for the cables if required. Areas with significant number of unmitigated boulders could lead to shallow/no burial of the cable leaving it exposed to external hazards such as fishing, shipping and on-bottom stability. Some remedial measures for protecting exposed/reduced burial areas of cable are listed below.

<u>Rock fill protection</u>: a rock berm could be specifically designed with sufficient height to cover and protect the cable. Rock berms are installed using specific vessels fitted with a fall pipe, used to place the rocks on the seabed over a cable.

<u>Rock Bags</u>: bags are placed on top of a cable to create a layer of protection. The bags are made from a durable material, often high strength geotextile or heavy-duty mesh, and filled with rocks of a specific size and weight to make them suitable to the local environment.

<u>Concrete Mattressing</u>: concrete or steel mats are placed over an exposed cable. The mats are generally made of heavy-duty panels that are interconnected to form a solid layer over a cable. These panels are designed to withstand the weight of the seabed and any external forces that may be encountered.

<u>Cable Protection Systems (CPS)</u>: such as tubular protective sleeves that can be fitted around a cable to provide additional protection/armouring. These sleeves can be made from various materials, can be either flexible or rigid and are normally fitted during cable lay operations. Tubular sleeves are more susceptible to external hazards, such as anchoring, and are often used in combination with mattresses or rock placement.

Table 3. Advantages and disadvantages of commonly used trenching tools, with regards to boulders.

Tool	Advantages	Disadvantages
Jet Trencher	Fitted with retractable swords which can lift and/or widen the separation distance during trenching, potentially allowing for the swords to bypass any encountered boulders. Potential for remedial passes, should burial not be achieved on the first pass.	Contractors generally state that boulders >0.3 m will potentially impact burial. However high densities of boulders of smaller dimensions would also be problematic. Dependent on Contractor. If larger boulders are encountered, the jet swords could be damaged and a reduction in depth of lowering is observed.
Mechanical Trencher	Trencher may be able to manoeuvre boulders, depending on the soil type/matrix and size of the cutting chain. Should a boulder be encountered the mechanical cutting boom can be retracted, continuing burial albeit at a reduced burial depth.	Contractors generally state that boulders >0.3 m will potentially impact burial. However high densities of boulders of smaller dimensions would also be problematic. Dependent on Contractor. Boulders may generally lead to reduced lowering. Encountering boulders may result in cutting chain wear and cause damage to the cutting chain picks. If an area cannot be trenched due to significant density of boulders, the trencher would have to unload cable, recover and reposition, resulting in exposed cable and increased duration in operations.
Cable Plough	Cable ploughs generally have the capability to push the boulders to one side out of the cable lay path, depending on size and position.	Ploughs are generally not suitable for inter-array cables, as the vessel is forced to veer off on approach to WTG, leaving a section of un-buried/surface laid cable. Large boulders can misalign ploughs/plough ride out.

3 EXAMPLE THEORETICAL STUDY

When choosing the most appropriate mitigation method, it is likely that a combination of all of the above steps will be required in order to sufficiently mitigate the risk. The following describes a potential theoretical mitigation strategy following a survey, designed to identify the required range of boulders within a corridor wide enough to have a high likelihood of successful cable route engineering.

An export cable is to be installed through an area with identified (Identify - Step 1) surface and sub-seabed boulders, using the example from Figure 2. The original route is shown as a red line. Route engineering (Avoid - Step 2), has been carried out by avoiding any hard constraints (large boulders >~2 m) and choosing the shortest path through boulder fields, where possible. The optimised route is shown as black line Figure 4.

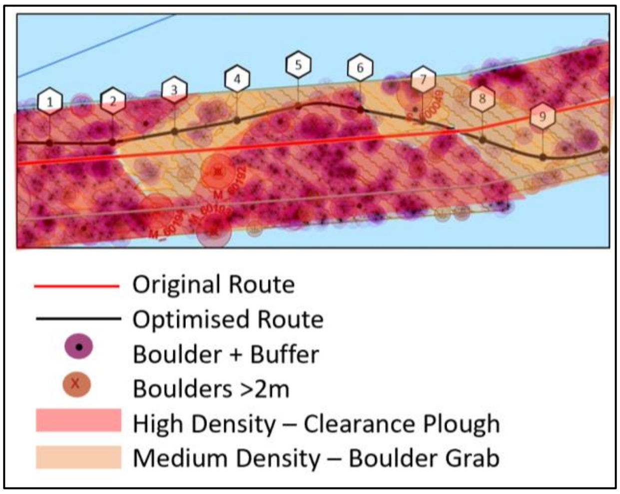

Figure 4. Example strategy.

Once the most optimum route is designed, and if boulders still pose a risk to the cable, removal/ clearance should be considered (Relocate - Step 3). As seen in Figure 4, a BG might be more suitable for the medium dense areas (e.g., between KP6 and KP8), whereas a CP would be more suited in denser areas (e.g., between KP1 and KP2). However, this will depend on distance between areas. In practice, a CP might be used for the full extent.

For Step 4 and 5 (Reduce and Remediate), the most suitable installation tool should be selected taking into consideration the ground conditions along the route, including any areas of boulders that could not be avoided or cleared by the above steps. For these 'un-cleared' areas, an allowance for remedial protection such as rock placement should be considered.

4 CONCLUSIONS

Whilst it is not always possible to remove the risk boulders pose to submarine cables entirely, the positive implications of investing project time and costs early on by following a mitigation strategy has proven to reduce unforeseen additional time and costs later on in a project.

Ensuring the most suitable detection method is chosen at the identification stage, as part of a survey campaign, is critical in detecting and measuring the presence of boulders. As part of the proposed Boulder Mitigation Strategy, the dimensions and distribution of boulders along a cable route is also key for selecting the most appropriate boulder clearance tool(s), if required. Poor selection of clearance tools can lead to downtime for several reasons i.e., tool damage etc.

If boulders remain a risk to the site and cannot be mitigated against employing the suggested strategy, it is important additional costs and time are factored into a project to accommodate the continually monitored risk of an unknown but expected boulder encounter.

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